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Formability in AA5083 and AA6061 alloys for light weight applications

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ABSTRACT

With recent development in the automotive and aerospace industries, the lightweight, yet inexpensive aluminum alloys are of great demand in industrial applications. In this paper, considering the limited applications in non-superplastic materials, two typical alloys of AA5083 and AA6061 were investigated and compared during high temperature tensile tests to study their formability. The results of tensile tests and microstructures were shown, which indicated the deformation properties under different conditions. Both alloys exhibited relatively weak strain hardening effects especially at relatively lower strain rates. Furthermore, the highest strain rate sensitivity index (m value) was obtained, and the peak of percent elongation-to-failure also coincided with the ranges of highest m value. The flow stress coupled with the dynamic grain growth was related with the temperatures and strain rates. The grains appeared to be coarser in the deformed samples. Cavitation and recrystallization have also been found as a result of strain rate and temperature.

1. Introduction

Superplastic materials are polycrystalline solids which have the capability to undergo large plastic strains, often in excess of 200% prior to failure [1]. Over past several decades, aluminum alloys with superplasticity were widely studied for light weight applications. In order to obtain great formability and mechanical properties, the materials with superplasticity are specially prepared. A lot of processing approaches including rolling, forging, extrusion, equal channel angular pressing (ECAP), friction stir processing (FSP) and various techniques have been used to produce fine recrystallized grain size and the observation of superplasticity [2–7]. However, those thermo-mechanical processing methods limit the wider usage of superplastic forming (SPF) to great development due to relatively more time and higher cost [8]. Based on the limitations, a more formable material with fine and stable structure but low cost is needed, and it also expands the conventional materials to be used in SPF applications.

Generically, the aluminum alloys of heat-treatable and high strength are common used materials, such as 7075, 7475, 2024, 5083 and 6061 [1]. As a commercial alloy with corrosion resistance and moderate to high strength, the 5083 aluminum alloy is widely applied in sheet forming processes [2]. Additionally, the 6061 aluminum alloy has been studied extensively because of its benefits such as moderate strength, good formability and corrosion resistance.

In this paper, rolled AA5083 and AA6061 were utilized as two typical non-superplastic materials and were investigated during high temperature tensile tests to study their formability. The results of the tensile test coupled with optical microscopy have been investigated, which indicate the deformation properties under different conditions. The flow stress as a function of temperature and strain rate has been shown to establish the formability of these two alloys. Furthermore, the highest strain rate sensitivity index (m value) is obtained to verify the feasibility of these two alloys. Microstructures including cavitation and recrystallization have also been found as a result of different strain rates and temperatures.

2. Experimental details

Rolled AA5083 and AA6061 sheets with thickness of 3 mm were used for high temperature tensile tests and microstructure observations. Tensile specimens with 20 mm gauge length and 4 mm gauge width were machined from the sheets. In order to obtain better formability during test, all the AA5083 and AA6061 specimens have been annealed for 2 h at 345 °C and 415 °C, respectively. For AA5083, an aging treatment at 150 °C for 24 h was proved to be helpful to successfully reveal the microstructure by decorating the grain boundary with precipitates [9]. The samples were then mechanically polished and etched with Graf Sergeant reagent (15.5 ml HNO_3, 0.5 ml HF, 3 g Cr_2O_3 and 84 ml H_2O). For AA6061, the Poulton's reagent-solution, (1) 50 ml solution of 15 ml HCl, 30 ml HNO_3, 2.5 ml HF and 2.5 ml H_2O, (2) 25 ml

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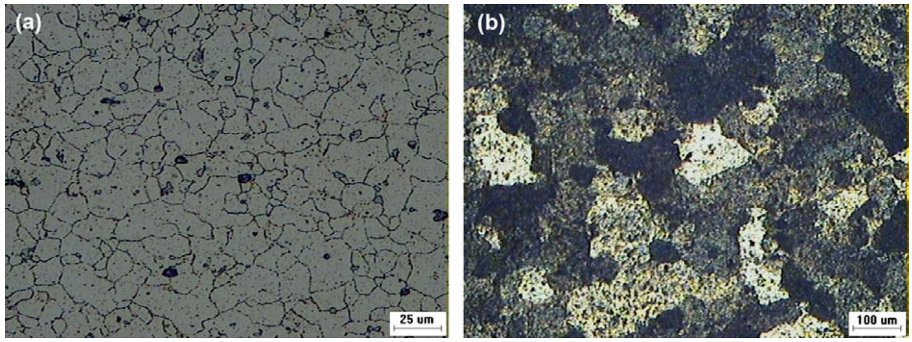

Fig. 1. Micrographs of (a) AA5083 and (b) AA6061 in the annealed condition.

HNO_3, (3) 40 ml of solution of 3 g chromic acid per 10 ml of distilled water [10], was used for microstructure etching.

Fig. 1 shows the typical optical microstructure of AA5083 and AA6061 in the annealed condition. The grains were fairly equiaxed. The grain size was measured by the linear intercept method [4]. It is about 13.6 μm and 115 μm in average size, respectively, for AA5083 and AA6061.

Uniaxial tensile tests of the specimens were performed using Instron 8500 testing machine equipped with an electrical resistance furnace chamber. The specimens were tested in the temperature range of 300 °C, 400 °C and 500 °C at constant crosshead displacement velocity, with the corresponding initial strain rate from 0.0001 s^{-1} to 0.3 s^{-1}.

3. Results and discussion

3.1. High temperature tensile tests

Fig. 2 shows the true stress–strain plots for a series of initial strain rates at temperature of 300 °C. It can be observed from Fig. 2, for both materials, the stress appears to increase with decreasing strain rate. It has been reported that the enhanced strain hardening at slower strain rates may be because of dynamic grain growth [9]. This can be found in AA5083, since it behaved enhanced strain hardening at strain rate of 10^{-4} s^{-1} due to great grain growth during high temperature deformation. However, generally the curves exhibit relatively weak strain hardening effects especially at strain rates lower than 0.1 s^{-1}. The curves show the similar profiles at different initial stain rates under higher temperature of 400 °C or 500 °C.

The flow stresses as a function of strain rate at different temperatures are plotted in Fig. 3. For both materials, it can be found that the curves show typical sigmoidal profiles. The flow stress increases with increasing strain rate. Also, the two materials differ greatly, especially during high strain rates.

The strain rate sensitivity index (m value), calculated from slopes of the log stress vs. log strain rate ($m = d\log\sigma/d\log\dot{\varepsilon}$) [9], are plotted in Fig. 4, respectively. The main trends for data on m value are as follows.

(1) Generally, the m value peak increases as the temperature increases (except AA5083) as a result of weak strain hardening and grain growth effects during testing at 300 °C, the alloy has high stress at higher strain rate but low stress at lower strain rate.
(2) For superplastic behavior, m value would be greater than or equal to 0.3 [1]. Unlike the superplastic materials, both AA5083 and AA6061 show the maximum values at higher strain rate. A maximum m value of 0.41 is obtained for AA5083 at 300 °C, while 0.24 for AA6061 at 500 °C.

The percent elongation-to-failure is used as a measure of the formability of the material and is typically a function of strain rate and temperature. The tensile elongations for both alloys plotted as a function of log initial strain rate are shown in Fig. 5. Generally, the tensile elongation increases with increasing strain rate and test temperature. This trend is different from the superplastic materials with slower strain rate showing larger percent elongation-to-failures [5–7,11]. However, the elongations do not vary a great deal for different strain rates during test at 300 °C or 400 °C. That is probably due to less cavitation and weaker strain hardening effects especially at high strain rates. There are much more cavities and grain growth at 500 °C. The largest percent elongation-to-failure is 93.25% and 69.00%, respectively, for AA5083 and AA6061 at 500 °C. Besides, the m value confers a high resistance to neck

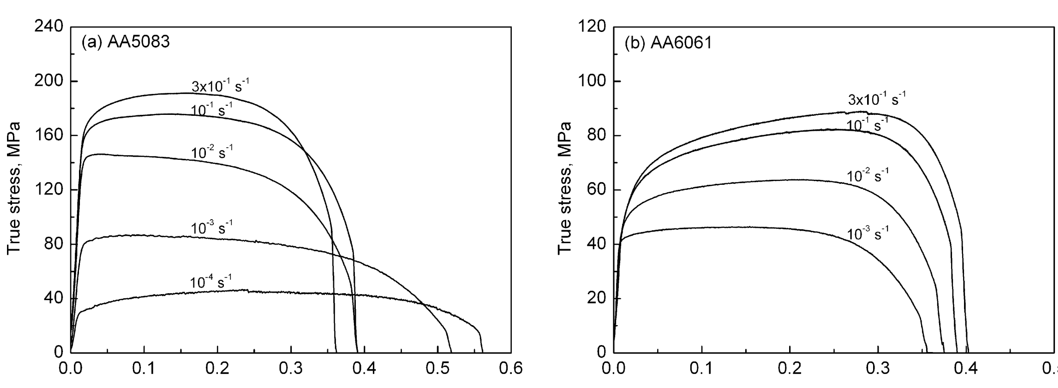

Fig. 2. True stress–true strain tensile test curves at 300 °C and various initial strain rates of (a) AA5083 and (b) AA6061.

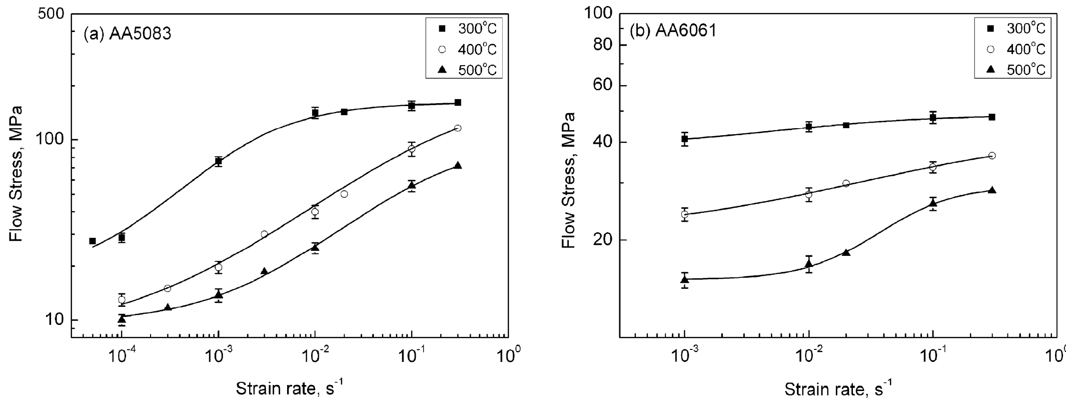

Fig. 3. Strain rate dependence of flow stress at different temperatures.

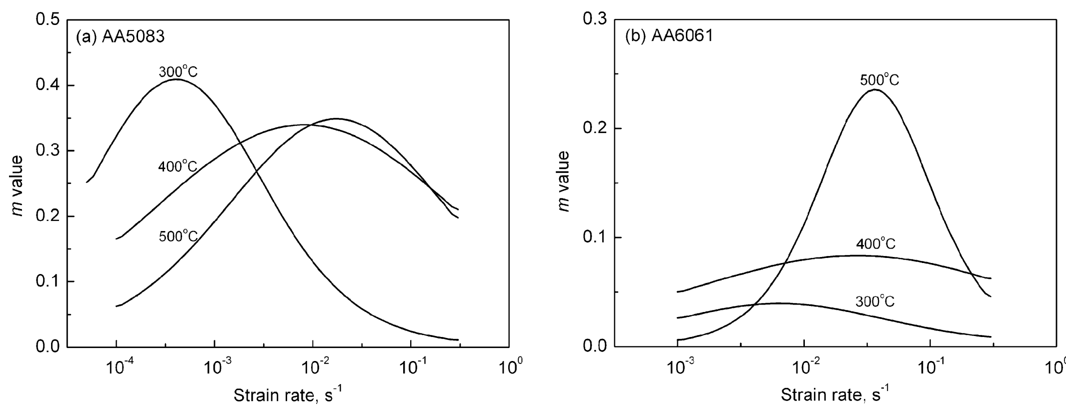

Fig. 4. The *m* values plotted as a function of log strain rate at different temperatures.

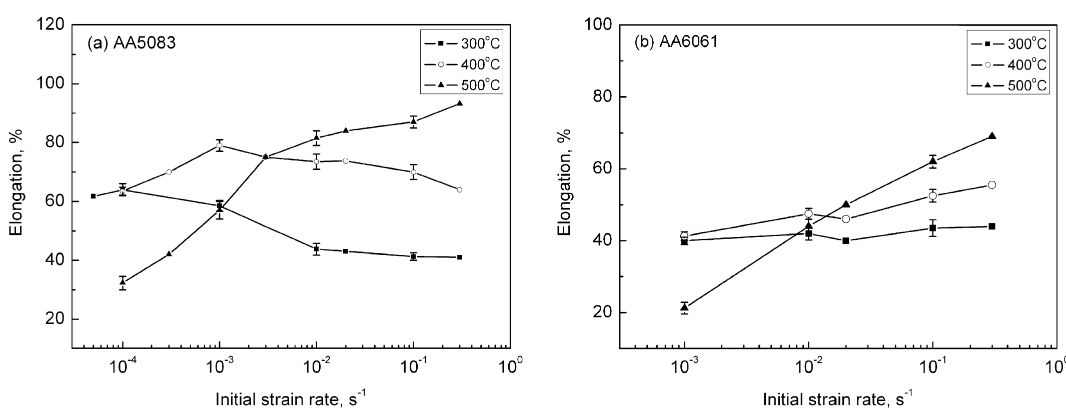

Fig. 5. Tensile percent elongation-to-failure as a function of initial strain rate at different temperatures.

development and results in the high tensile elongations [1], so that the maximum elongation coincides with the ranges of highest *m* value distributions.

3.2. Microstructure

Typical micrographs of AA5083 tested at 300 °C and initial strain rate of $10^{-4}\ s^{-1}$ in the grip and gauge regions are shown in Fig. 6. As expected, the grains appear coarser in the samples deformed at high temperature due to the grain growth. The increase in grain growth caused by different temperature is evident by comparing the microstructure with Fig. 7. Similar to the superplastic materials [11], the alloy shows much more grain growth at 500 °C. The average grain size of grip region is about 22.5 μm at 300 °C in Fig. 6a, while some of the grains grow as big as 200 μm at 500 °C in Fig. 7a. The microstructure also contains a wide range of grain sizes, which are composed of the new, smaller grains formed due to recrystallization. It is noted that the grains have higher aspect ratio along the tensile direction after testing at 300 °C.

Cavitation has been observed in a lot of alloys including those based on aluminum, copper, iron, lead, silver, titanium and zinc.

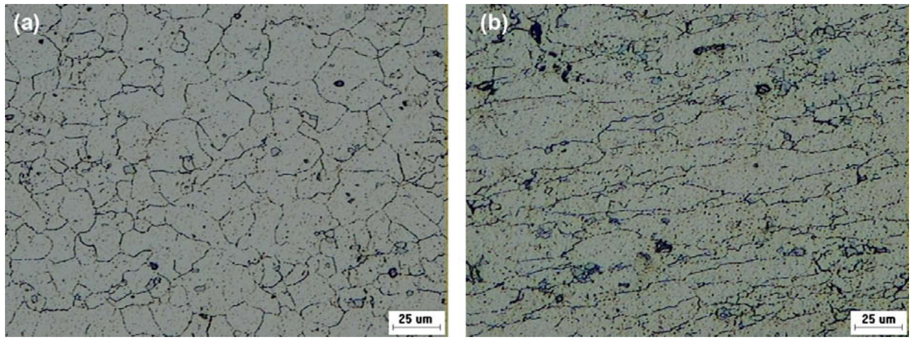

Fig. 6. Microstructures of AA5083 tested at 300 °C and initial strain rate of 10^{-4} s^{-1}; (a) grip and (b) gauge regions.

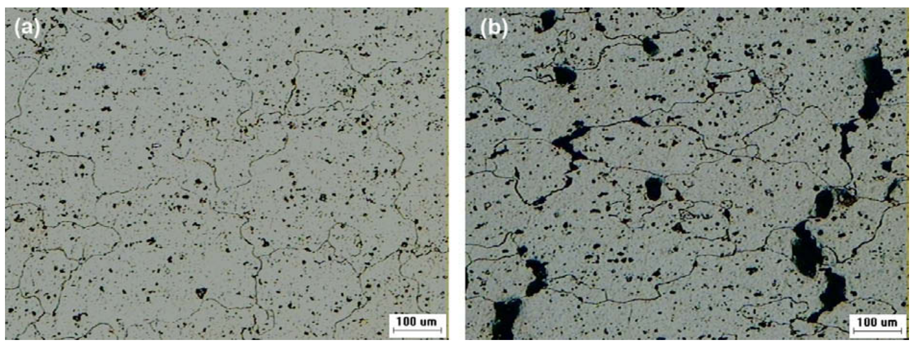

Fig. 7. Microstructures of AA5083 tested at 500 °C and initial strain rate of 10^{-4} s^{-1}; (a) grip and (b) gauge regions.

The cavity is an internal void, which is located on the grain boundary. Failure during deformation occurs as a result of the nucleation, growth and coalescent of internal cavities [1]. Generally, as an important requirement, tensile stress plays a great role for cavitation occurrence and growth. Little cavitation was observed in the grip region from Fig. 7a because of low tensile stress at this area, while much more and larger cavities were produced in the gauge region after tensile test from Fig. 7b. It has been reported that the failure is mostly due to internal cavitation at the lower strain rates; but it changes to external necking at higher strain rates [11]. As a result, there are more cavities with the decrease in strain rate. The fracture tip has a jagged appearance especially at low strain rates. This is most likely because the sample fractures along the intergranular cavities as shown in Fig. 7b. Besides the tensile stress, there appears to be an effect of temperature on the amount of cavitation, with higher temperature showing more cavitation than that of lower temperature. Comparing the microstructures at 300 and 500 °C, it is found that there are much more cavities and growth at 500 °C (Figs. 6 and 7).

Although neither of the two non-superplastic materials has high elongation-to-failure of superplastic materials, the relative low flow stress, ductility, microstructure, temperature and strain rate can be considered for their good formability. Hence, the good formability could be applied by using these non-superplastic materials to exploit a forming technology that does not require full superplasticity.

4. Conclusions

AA5083 and AA6061 specimens have been annealed for testing the formability at high temperatures and different strain rates. The conclusions are summarized as follows.

1. Both the alloys exhibit relatively weaker strain hardening effects especially at relatively lower strain rates. Generally, the flow stress increases with increasing strain rate.
2. The *m* value peak increases as the temperature increases, except AA5083 at 300 °C. Both AA5083 and AA6061 show the maximum values at high strain rates. A maximum *m* value of 0.41 is obtained for AA5083 at 300 °C, while 0.24 for AA6061 at 500 °C.
3. The largest percent elongation-to-failure is 93.25% and 69.00%, respectively, for AA5083 and AA6061 at 500 °C. This peak of elongation also coincides with the range of highest *m* value.
4. The grains appear to be coarser in the samples deformed due to the grain growth at the high temperatures. For AA5083, the grain size is about 13.6 μm in annealed condition, while it increases to 22.5 μm at 300 °C and as big as 200 μm at 500 °C.
5. Recrystallization took place during deformation. There are more cavities showing growth and coalescence of the cavities over time at higher temperatures and lower strain rates. The sample fractures along the intergranular cavities.

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